Quasi-Final Agenda for
Image Analysis and Understanding Data from Scientific Experiments

Los Alamos National Laboratory, 2-6 December 2002

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Workshop webpage

http://cnls.lanl.gov/Conferences/ImageAnalysis/

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10:30 - 11:30 Peyman Milanfar, **Some Performance Limits in Imaging and Image Processing**

11:30 - 12:30 Tony Chan, **PDE and Wavelet Techniques for Image Compression**

12:30 - 2:00 Catered lunch

2:00 - 3:00 Chris Borel, **Challenging image analysis problems in the exploitation of hyperspectral remote sensing data for the visible and infrared spectral region**

3:00 - 4:00 Andrea Bertozzi, **Fourth Order Equations in Image Processing**

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7:30 - 8:00 Coffee, tea, and pastries

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9:00 - 10:00 Luminita Vese, **Image Segmentation Using Level Sets and Energy Minimization Techniques**

10:00 - 10:30 Break

10:30 - 11:30 Mark Green, **The Statistics of Natural Images, the TV Algorithm and Image Denoising**

11:30 - 12:30 Alan Yuille, **Order Parameters for the Detection of Target Curves**

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2:00 - 3:00 John Mosher, **Large Data Array Processing of MEG and EEG Data**

3:00 - 4:00 Jeff Fessler, **The Nonuniform FFT and its Applications in Tomographic Image Reconstruction**

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7:30 - 8:00 Coffee, tea, and pastries

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9:00 - 10:00 Marios S. Pattichis, **AM-FM Analysis of Medical Images**

10:00 - 10:30 Break

10:30 - 11:30 Jackie Shen, **Total Variation Based Bayesian Video Dejittering**

11:30 - 12:30 Richard Leahy, **Quantitative PET Image Reconstruction**

12:30 - 2:00 Catered lunch

2:00 - 3:00 James Theiler, **Using Machine Learning to Label Pixels in Remote Sensing Imagery**

3:00 - 4:00 Andrew Fraser, **Augmenting image classification metrics with tangents to invariances**

4:00 - 4:30 Break

4:30 - 5:30 Guillermo Sapiro, **Image Inpainting**

1.4 Thursday

1.4.1 Short Course I: PDE and Variational Methods for Image Analysis

7:30 - 8:00 Coffee, tea, and pastries

8:00 - 9:00 Kevin R. Vixie, **PDEs, Variational Methods, and Image Analysis: Introduction and Background Material**

9:00 - 10:00 Guillermo Sapiro, **PDEs on Surfaces**

10:00 - 10:30 Break

10:30 - 11:30 Luminita Vese, **Texture Modeling with Total Variation Minimization and Oscillating Patterns in Image Processing**

11:30 - 12:30 Richard Tsai, **Level Set methods: Introduction and Examples**

12:30 - 2:00 Catered lunch

2:00 - 3:00 Tilak Ratnanather, **Computing Metric Distances Between Shapes and the Euler-Poincaré equations of Computational Anatomy**

3:00 - 4:00 Andrea Bertozzi, **Navier-Stokes, Fluid Dynamics, and Image and Video Inpainting**

4:00 - 4:30 Break

4:30 - 5:30 Jackie Shen, **Inpainting and Prior Models**

1.5 Friday

1.5.1 Short Course II: Wavelet-based Methods for High Dimensional Data

(Due to a family medical situation that has just come up it seems likely that Jackis Shen and Michelle Quirk will give replacement tutorials for Gil Strang)

7:30 - 8:00 Coffee, tea, and pastries

8:00 - 9:00 Gil Strang, **Introduction to Wavelets I**

9:00 - 10:00 Jackie Shen, **Introduction to Wavelets II**

10:00 - 10:30 Break

10:30 - 11:30 Chris Brislawn **Wavelets in Image Coding**

11:30 - 12:30 Gil Strang **Filtering and Signal Processing**

12:30 - 2:00 Catered lunch

2:00 - 3:00 Song Chun Zhu, **Statistical Modeling of Visual Patterns II — Bridging Wavelet Models with Markov Random Fields**

(Friday Continued)

1.5.2 Short Course III: Stochastic Methods and Image Data

7:30 - 8:00 Coffee, tea, and pastries

8:00 - 9:00 Nick Hengartner, **Stochastic Image Modeling: an Introduction with an Emphasis on Markov Random Fields**

9:00 - 10:00 Song Chun Zhu, **Statistical Modeling of Visual Patterns I — From Statistical Physics to Vision Models**

10:00 - 10:30 Break

10:30 - 11:30 Alan Yuille, **Statistical Edge Detection: Learning and Evaluating Edge Cues**

11:30 - 12:30 Andy Fraser, **Information, Dynamics and the Modeling of Images for the Purpose of Compression**

12:30 - 2:00 Catered lunch

2:00 - 3:00 Jonas August, **Sketch inference as a theory of visual contour computation**

3:00 - 4:00 David Wilson, **A Statistical/Registration Approach to Echocardiographic Image Analysis**

2 Monday – Wednesday Talk Abstracts

Abstracts in presentation order.

Monday

On the Metrics and Euler-Lagrange Equations of Computational Anatomy
Michael Miller, Johns Hopkins University

The model we review of Computational Anatomy is a Grenander deformable template, an orbit generated from a template under groups of diffeomorphisms. The metric space of all anatomical images is constructed from the geodesic connecting one anatomical structure to another in the orbit. The variational problems specifying these metrics are reviewed along with their associated Euler-Lagrange equations. The Euler equations of motion derived by Arnold for the geodesics in the group of divergence free volume-preserving diffeomorphisms of incompressible fluids are generalized for the larger group of diffeomorphisms used in CA with nonconstant Jacobians. Metrics that accommodate photometric variation are described extending the anatomical model to incorporate the construction of neoplasm.

Relevant papers include:

Grenander and Miller, *Computational Anatomy: An Emerging discipline*, Quarterly of Applied Mathematics, 1998.

Miller and Younes, *Groups actions, Homeomorphisms, and Matching: A General Framework*, IJCV, 2001.

Miller, Trouve and Younes, *On the metrics and Euler-Lagrange Equations of computational Anatomy*, Annual Review of Biomedical Engineering, 2002.

Some Performance Limits in Imaging and Image Processing
Peyman Milanfar, UC-Santa Cruz

It is of interest in many tasks in image processing and analysis, particularly from of scientific data, to know the limits to how well a certain object or quantity can be detected or estimated. While a multitude of algorithms have been developed for varied tasks such as motion estimation or image segmentation or resolution enhancement, relatively few results are available that put the performance of these many algorithms into proper perspective by comparing them to limits or bounds on such performance, as derived from first principles. I will describe in this talk some of our work in this direction as it relates to the problem of image resolution enhancement and techniques associated with it.

PDE and Wavelet Techniques for Image Compression
Tony Chan (Math Dept, Univ. Calif. At Los Angeles) (Joint work with Dr. Haomiin Zhou at Caltech)

In this talk, I will present an overview of our recent work on combining PDE and wavelet techniques for image compression. The first part will be on an adaptive ENO wavelet transform designed by using ideas from Essentially Non-Oscillatory (ENO) schemes for numerical shock capturing. The second part of the talk is on using a variational framework, in particular the minimization of total variation (TV), to select and modify the retained standard wavelet coefficients so that the reconstructed images have fewer oscillations near edges.

Challenging image analysis problems in the exploitation of hyperspectral remote sensing data for the visible and infrared spectral region
Chris Borel, LANL

With the proliferation of imaging hyperspectral sensors on airplanes (e.g. AVIRIS, HyMap, HYDICE, ASAS, CASI, SEBASS, HIRIS, APEX) and space based sensors (e.g. Hyperion, LISA, MERIS, CHRISS, FTHSI, PRISM) image processing of hyperspectral data with 100-500 spectral channels is becoming increasingly important.

In this talk I will cover what I feel are current challenges in the analysis of hyperspectral data obtained in the visible and infrared:

(1) Atmospheric correction is a crucial analysis step. In the visible and short wave infrared (0.4 - 2.5 micrometer) the at sensor radiances need to be converted to surface reflectances which requires estimation of the atmospheric absorption and scattering through parameters (aerosol optical depth, water vapor), correction for the effect of bi-directional reflectance distribution function, blurring due to the adjacency effect and retrieval of reflectance in shadows. In the mid-wave (3-4 micron) and long-wave infrared (7.5-13.5 micron) spectral region we need even more information about the atmosphere (temperature and water vapor profile, ozone amount) to retrieve quantities of interest such as

skin temperature, surface emissivity and gas plume absorptions. An overview of challenges and the methods developed at LANL and the Air Force Research Laboratory will be presented.

(2) Many hyperspectral instruments are not perfect and have artifacts which need to be mitigated or any sophisticated analysis might fail. A staring imaging Fourier transform instrument in the infrared might have a non-linear detector, spatial jitter, spectral mis-registrations due to optical path differences and even experience non-uniform sampling of the interferograms. Grating spectrometers might exhibit subtle spectral shifts, changes in width of the spectral response and slow time varying drifts in gain and offsets for each pixel. We will show some examples of simulated artifacts and their removal.

(3) Analyzing reflectance and emissivity data for a pixel containing multiple materials (with potentially different surface temperatures!) is very challenging at the usual 2-500 m pixel scale since for a 3-d structure such as vegetation the measured reflectance is often not just the sum of the fractions of each material (e.g. leaves and soil) multiplied with its reflectance or emissivity spectrum. However knowing the fractions of e.g. vegetation and soil is of importance to a environmental researcher to monitor the environment or estimate the amount of biomass. Sometimes users of hyperspectral imagery want even more sophisticated information such as the leaf chemical content (nitrogen, proteins, lignin and water) retrieved from hyperspectral data.

Many of the listed challenges need to be addressed in future remote sensing research. While this talk attempts to present some potential solutions to the image analysis problems many of them remain open and unsolved.

Fourth Order Equations in Image Processing
Andrea Bertozzi, Duke University

(Andrea's abstract here)

Visual Inference by Data-Driven Markov Chain Monte Carlo
Song Chun Zhu, UCLA

(Song Chun's abstract here)

Tuesday

The Level Set Method — What's in it for You?
Stan Osher, UCLA

The level set method for capturing moving fronts was introduced in 1987 by Osher and Sethian. It has proven to be phenomenally successful as a numerical device. For example, typing in "Level Set Methods" on Google's search engine gives roughly 3200 responses. Applications range from capturing multiphase fluid dynamical flows, to special effects in Hollywood to visualization,image processing, control, epitaxial growth, computer vision and many more. In this talk we shall give an overview of the numerical technology and a few image processing applications.

Image Segmentation using Level Sets and Energy Minimization Techniques
Luminita Vese*, Tony Chan and Stan Osher, UCLA

(Luminita's abstract here)

The Statistics of Natural Images, the TV Algorithm and Image Denoising
Mark Green, IPAM

(Mark's abstract here)

Order Parameters for the Detection of Target Curves
Alan Yuille, UCLA

We consider the task of detecting a target in a cluttered background. The problem is formulated in general but we specialize to the specific tasks of tracking a contour – such as a road in an aerial image. We determine order parameters, which depend on statistical properties of the target and domain, that characterize the difficulty of the task independently of the algorithm employed to detect the target. For the road tracking problem, we show that there is a phase transition at a critical value of the order parameter – above this phase transition it is impossible to detect the target by any algorithm. In related work, we derive closely related order parameters which determine the complexity of search and the accuracy of the solution using the A* search strategy.

Large Data Array Processing of MEG and EEG Data
John C. Mosher, LANL

Magnetoencephalography (MEG) measures the extremely weak quasistatic magnetic field outside the scalp generated by neural activity within the brain; electroencephalography (EEG) measures the scalp potentials from the same activity. The forward problem is the calculation of the external fields given an elemental source within the brain, for which the solution is analytic for spheres and more generally solved using numerical methods for tessellated shapes. Because the fields are nearly static, the forward models are specializations of the Newtonian potential measured from a distance, and therefore the inverse solution is ambiguous, without the imposition of strong models. In practice, the fields are measured at a few hundred sites about the upper hemisphere of the head, in the presence of substantial environmental and biological noise, and sampling rates and filtering protocols restrict the bandwidth to about 100 Hz, recorded on the order of ten minutes. Magnetic resonance images are used as anatomical basis sets on which to project most of the present day functional solutions. We review the basics of the acquisition systems and forward modeling, then focus on the inverse modeling approaches used to process these large spatiotemporal data matrices.

The Nonuniform FFT and its Applications in Tomographic Image Reconstruction

Jeffrey A. Fessler* and Bradley P. Sutton, University of Michigan

The FFT is used widely for computing the Fourier transform (FT) at uniformly- spaced frequency locations. However, in many imaging applications one needs nonuniform frequency sampling. Several papers have described fast approximations for the nonuniform FT based on interpolating an oversampled FFT. We present a method for the nonuniform FT that is optimal in a min-max sense. The proposed method minimizes the worst-case approximation error over all unit-norm signals. Unlike some previous methods for the nonuniform FT, the proposed method easily generalizes to multidimensional signals. We illustrate applications of this method in computed tomography and magnetic resonance imaging.

Tomographic Reconstruction of Dynamic Objects

Yonggang Shi* and W. Clem Karl, Boston University

Dynamic tomography is a challenging inverse problem arising in various areas, for example, the reconstruction of time varying tracer distributions in nuclear medicine. The main challenges arise due to a sparsity of projection data and the ill-conditioned nature of the tomographic operator. We propose a variational framework based on object models to overcome these difficulties. In our framework, each image of the sequence is modeled as consisting of an object region and a background region. The boundary of the object region is represented as a continuous curve. The dynamics of the image sequence is captured through the dynamics of both the object boundary and the region intensities. An energy function is then constructed as the sum of four terms: a data fidelity term, a prior object geometry term, an object boundary dynamic term based on an affine dynamic model, and a term for intensity dynamics. We then jointly solve for the dynamic object shape and intensities based on the observed set of projections acquired over time by minimizing this energy. To solve this nonlinear optimization problem, a coordinate descent algorithm is developed which alternately minimizes the energy with respect to the object geometry parameters and the intensities. Efficient level set methods are used to evolve curves in the gradient descent directions to minimize the energy. Preliminary experimental results will be presented to demonstrate that our approach allows robust reconstruction of dynamic object sequences from extremely limited projection data acquired over time. Extensions to unknown object dynamic models will also be discussed.

Wednesday

Object-Adaptive Time-Sequential Imaging for Dynamic Scenery: Application to Cardiac MRI

Nitin Aggarwal and Yoram Bresler, UIUC

Imaging of time-varying (dynamic) objects is often subject to the so-called time-sequential constraint i.e. one can sample the object at only one "spatial" location at any given time instant. This arises in systems that involve mechanical or electronic scanning, including radar or acoustic imaging or tomography and magnetic resonance imaging (MRI) of dynamic objects. In such a system the ability to reconstruct the original object from the acquired samples depends not only on the (spatial and temporal) density of samples but also on the order in which the sequence of samples are acquired.

Time-Sequential Sampling (TSS) theory [1] enables one to to design the minimum-rate sampling sequence required based on the spatio-temporal model of the object specified in terms of it's spatial and spectral supports. A reconstructive algorithm to recover the object from the samples is also specified. Therefore an adaptive TSS imaging scheme involves the following steps, (1) Estimation of the support information either experimentally or based on a priori knowledge, (2) adaptation of the sampling sequence, (3) conducting the experiment to acquire the required samples, (4) reconstruction of object based on estimated support and acquired samples.

In the presentation, we will discuss the time-sequential sampling theory and illustrate it's application in cardiac MR imaging [2,3].

References: [1] N.P. Willis and Yoram Bresler, "Lattice theoretic analysis of time-sequential sampling of spatio-temporal signals. part I and II,",IEEE Trans on Info. Theory, pp. 190–220, 1997.

[2] Nitin Aggarwal, Qi Zhao, and Yoram Bresler,"Spatio-temporal modeling and minimum redundancy adaptive acquisition in dynamic MRI,", Proc. ISBI, 2002, pp. 737–740.

[3] Qi Zhao, Nitin Aggarwal, and Yoram Bresler,"Dynamic imaging of time-varying objects,", Proc. of ISMRM, p. 1776, 2001.

AM-FM Analysis of Medical Images
Marios S. Pattichis, UNM

Amplitude-Modulation Frequency-Modulation (AM-FM) models allow us to describe continuous-scale variations in digital images. Frequency Modulation allows us to describe images in terms of an underlying curvilinear coordinate system that describes the continuous variation in instantaneous frequency content. Amplitude Modulation is used for describing the brightness (envelope) variation. AM-FM expansions are defined in terms of the estimated curvilinear coordinate system and the estimated amplitude function.

We describe three applications of AM-FM models in medical imaging. We show examples from Electron Microscopy, chest radiographs, and Motion Mode (M-mode) ultrasound video. In Electron Microscopy, we present an application of an Amplitude Modulation - Frequency Modulation (AM-FM) image representation in segmenting electron micrographs of skeletal muscle for the recognition of: (i) normal sarcomere ultrastructural pattern, and (ii) abnormal regions that occur in sarcomeres in various myopathies. A number of different image structures can be visualized by simple thresholding of the one-dimensional histograms of the instantaneous frequency magnitude and amplitude.

A second example of image enhancement in chest radiographs is also presented. In this example, we show how the instantaneous frequency magnitude and the amplitude images can be used to extract lung opacities from chest radiographs. Lung opacities are seen as low instantaneous frequency magnitude and high amplitude regions.

As a third example, we present an AM-FM analysis system for analyzing M-mode (Motion mode) ultrasound video. A sum of FM harmonics is used for visualizing the cardiac wall boundaries. The estimated frequency-modulation (fm) process is shown to capture the cardiac wall deformation, while the amplitude modulation process is shown to follow changes in cardiac wall material. Results from segmenting the septum and left-ventricle walls are also presented.

Total Variation Based Bayesian Video Dejittering
Jackie Shen, University of Minnesota

(Jackie's abstract here)

Quantitative PET Image Reconstruction
Richard Leahy, USC

(Richard's abstract here)

Using Machine Learning to Label Pixels in Remote Sensing Imagery
James Theiler, LANL

(James' abstract here)

Augmenting image classification metrics with tangents to invariances
Andrew Fraser, Brendt Wohlberg, Nicolas Hengartner, and Kevin R. Vixie, LANL

I present a report on work in progress concerning the use of tangent approximations to invariances. We augment image classification metrics in a principled way using the first and second order local approximation. The result is a metric which is modified to reflect the nonlinear nature of the invariances, yet is still computationally efficient in implementation. Preliminary results are presented.

Image Inpainting
Guillermo Sapiro, University of Minnesota

(Guillermo's abstract here)

3 Short Courses: Abstracts and Overview

In this section the abstract for the short courses are given in the presentation order.

3.1 PDE/Variational Methods Short Course

PDEs, Variational Methods, and Image Analysis: Introduction and Background Material
Kevin R. Vixie, LANL

In this lecture, I will briefly introduce various aspects of PDE and variational methods with a view to image analysis beginning with a brief discussion of the image processing as an inverse problem. After introducing the necessary ideas from linear and nonlinear functional analysis and analysis, I will also more look closely at total variation minimization and at nonlinear diffusion (Perona-Malik).

PDEs on Surfaces
Guillermo Sapiro, University of Minnesota

(Guillermo's abstract here)

Texture Modeling with Total Variation Minimization and Oscillating Patterns in Image Processing
Luminita Vese and Stan Osher, UCLA

This talk is devoted to the modeling of real textured images by functional minimization and partial differential equations. Following the ideas of Yves Meyer in a total variation minimization framework of Rudin-Osher-Fatemi, we decompose a given (possible textured) image f into a sum of two functions $u+v$, where $u \in BV$ is a function of bounded variation (a "cartoon" approximation of f), while v is an oscillating function of zero mean, representing the texture or noise. To model v we use the space of oscillating functions introduced by Y. Meyer. The new algorithm is very simple, making use of partial differential equations and is easily solved in practice. Finally, we implement the method by finite differences, and we present various numerical results on real textured images, showing the obtained decomposition $u + v$. We will also show how the method can be used for texture discrimination and texture segmentation.

Level Set Methods: Introduction and Examples
Richard Tsai, Princeton University

(Richard's abstract here)

Computing Metric Distances Between Shapes and the Euler-Poincaré equations of Computational Anatomy
Tilak Ratnanather, Johns Hopkins University

Computational Anatomy is modeled as a Grenader deformable template which is an orbit generated from a template under the groups of diffeomorphisms. The solution of the Euler-Lagrange equations for inexact image matching in the tangent space of the manifold of diffeomorphisms gives the optimal flow field and thus the metric distance between the shapes. We will focus on i) derivation of the Euler-Lagrange equations for exact matching derived by Mumford and extended to inexact image matching by Miller & Younes ii) results of 1D numerical simulations using the Beg Gradient Method based on variations with respect to velocity, and finally iii) the Euler-Poincaré equations of Computational Anatomy that have connections with averaging models of fluid mechanics used by Holm, Marsden and colleagues.

Navier-Stokes, Fluid dynamics, and Image and Video Inpainting
Andrea Bertozzi, Duke University

Image inpainting involves filling in part of an image or video using information from the surrounding area. Applications include the restoration of damaged photographs and movies and the removal of selected objects. In this paper, we introduce a class of automated methods for digital inpainting. The approach uses ideas from classical fluid dynamics to propagate isophote lines continuously from the exterior into the region to be inpainted. The main idea is to think of the image intensity as a 'stream function' for a two-dimensional incompressible flow. The Laplacian of the image intensity plays the role of the vorticity of the fluid; it is transported into the region to be inpainted by a vector field defined by the stream function. The resulting algorithm is designed to continue isophotes while matching gradient vectors at the boundary of the inpainting region. The method is directly based on the Navier-Stokes equations for fluid dynamics, which has the immediate advantage of well-developed theoretical and numerical results. This is a new approach for introducing ideas from computational fluid dynamics into problems in computer vision and image analysis.

Inpainting and Prior Models

Jackie Shen, University of Minnesota

(Jackie's abstract here)

3.2 Wavelets and image Methods

Introduction to Wavelets I
Gil Strang, MIT

(Gil's abstract here)

Introduction to Wavelets II
Jackie Shen, University of Minnesota

(Jackie's abstract here)

Wavelets and Image Coding
Chris Brislawn, LANL

Filtering and Signal Processing
Gilbert Strang and Per-Olof Persson, MIT

We discuss two filters that are frequently used to smooth data. One is the (nonlinear) median filter, that chooses the median of the sample values in the sliding window. This deals effectively with "outliers" that are beyond the correct sample range, and will never be chosen as the median. A straightforward implementation of the filter is expensive for large windows, particularly in two dimensions (for images).

The second filter is linear, and known as "Savitzky-Golay". It is frequently used in spectroscopy, to locate positions and peaks and widths of spectral lines. This filter is based on a least-squares fit of the samples in the sliding window to a polynomial of relatively low degree. The filter coefficients are unlike the equiripple filter that is optimal in the maximum norm, and the "maxflat" filters that are central in wavelet constructions. Should they be better known....?

We will discuss the analysis and the implementation of both filters.

Statistical Modeling of Visual Patterns II — Bridging Wavelet Models with Markov Random Fields
Song Chun Zhu, UCLA

(Jackie's abstract here)

3.3 Stochastic Methods in Image Analysis

Stochastic Image Modeling: An Introduction with an Emphasis on Markov Random Fields

Nicolas Hengartner, LANL

(Nick's abstract here)

Visual Inference by Data Driven Markov Chain Monte Carlo

Song Chun Zhu, UCLA

(Song Chun's abstract here)

Statistical Edge Detection: Learning and Evaluating Edge Cues

Alan Yuille, UCLA

We formulate edge detection as statistical inference. This statistical edge detection is data driven, unlike standard methods for edge detection which are model based. For any set of edge detection filters (implementing local edge cues) we use pre-segmented images to learn the probability distributions of filter responses conditioned on whether they are evaluated on or off an edge. Edge detection is formulated as a discrimination task specified by a likelihood ratio test on the filter responses. This approach emphasizes the necessity of modeling the image background (the off-edges). We represent the conditional probability distributions non-parametrically and learn them on two different datasets of 100 (Sowerby) and 50 (South Florida) images. Multiple edges cues, including chrominance and multiple-scale, are combined by using their joint distributions. Hence this cue combination is optimal in the statistical sense. We evaluate the effectiveness of different visual cues using the Chernoff information and Receiver Operator Characteristic (ROC) curves. This shows that our approach gives quantitatively better results than the Canny edge detector when the image background contains significant clutter. In addition, it enables us to determine the effectiveness of different edge cues and gives quantitative measures for the advantages of multi-level processing, for the use of chrominance, and for the relative effectiveness of different detectors. Furthermore, we show that we can learn these conditional distributions on one dataset and adapt them to the other with only slight degradation of performance without knowing the ground truth on the second dataset. This shows that our results are not purely domain specific. We apply the same approach to the spatial grouping of edge cues and obtain analogies to non-maximal suppression and hysteresis.

Information, Dynamics and the Modeling of Images for the Purpose of Compression

Andrew M. Fraser, LANL and PSU

(Andy's abstract here)

Sketch inference as a theory of visual contour computation

Jonas August, Robotics Institute, Carnegie Mellon University

While complaints about the outputs of typical edge operators are common, systematic studies of the "perfect" edge map are rare, making the design of better algorithms difficult. To remedy this situation, we view visual contour computation as the estimation of a (clean) artist's sketch from a corrupted rendition, and we introduce the curve indicator random field (CIRF) as a idealized model of an artist's sketch. Intuitively, the value of the field is the amount of ink deposited by the artist's pen; technically, this random field is a superposition of local times of Markov processes that model individual curves. The explicit formulation of the CIRF enables the calculation of tractable formulas for its cumulants and moment generating functional, as well as the derivation of nonlinear filters for enhancing contour structure in noisy images. Specifically, the formulation leads to a coupled pair of reaction-diffusion-convection integro-elliptic partial differential equations for estimating the posterior mean of the CIRF.

But the framework also suggests we seek in natural images those correlations that were exploited by the filters for cleaning noise. We present the results of some edge correlation measurements that suggest that curvature has a role in contour enhancement. A Markov process model for contour curvature is therefore introduced, where it is shown that its most probable realizations include the Euler spiral, a curve minimizing changes in curvature. Contour computations with curvature highlight how our filters are curvature-selective, even when curvature is not explicitly measured in the input.

A Statistical/Registration Approach to Echocardiographic Image Analysis

David C. Wilson, University of Florida

Cardiac disease is the number one killer in the western world. The technology of echocardiography is the number one imaging modality for assessing the extent and progression of a patient's cardiac diseases. Reasons for acceptance of this technology include, cost, safety to the patient, real-time acquisition rates,

and portability of the device. Despite this acceptance, current clinical practice includes only a minimal number of measurements, which are usually made visually and subjectively. The reasons for the difficulty in making more quantitative and objective evaluations include image noise and dropout, confusing intracavitary structures, and rapid motion of cardiac walls. The goal of this tutorial is to describe recent advances in echocardiographic image analysis that have the potential to provide accurate and reliable quantitative measurements of important indices of cardiac health. These methods are based on statistical models generated from expert traced contours by the technique of Procrustes shape analysis. Since the thin-plate spline transformation can be used to map the image associated with one contour to the image associated with another, the images associated with a given collection of contours can be aligned so the model can be designed to incorporate image information as well. While this discussion is specific to echocardiographic images, the method is completely general and has a wide range of other applications. The techniques described in this talk are based on the work of D. Kendall, C. Taylor, F. Bookstein, and M. Sonka.

Key Words: image analysis, echocardiography, registration, Procrustes shape analysis, thin-plate spline transformation

4 Poster Session

The poster session is planned to be a central event of the workshop with a buffet dinner, drinks, hors d'oeuvres and desserts. The poster abstracts are arranged alphabetically according to the first authors last name.

Clustering Non-stationary Data via Adaptive Principal Component Analysis

Cynthia Archer, Oregon Graduate Institute

We develop a new signal modeling method, entropy constrained adaptive principal component analysis (ec-APCA), with sufficient flexibility to accurately model the cluster structure of real-world non-stationary data. Using a latent data framework, we derive a statistical model for a broad category of real-world signals that includes regions within images and measurements from natural processes. We model data of this type as a collection of low-dimensional patterns embedded in a high-dimensional observation or measurement space. We use this statistical model to drive development of our ec-APCA algorithm. This algorithm adjusts model parameters to minimize dimension reduction error between the model and sample data subject to a constraint on model entropy.

We evaluate the quality of models produced by our method using image texture data. Compared to spherical models (e.g. K-means clustering) and full covariance (i.e. Gaussian mixtures) models, ec-APCA proves to be a more effective tool for analyzing and identifying textures. Our results show that both spherical and adaptive PCA models segment texture images accurately with less than 2% classification error, whereas full covariance models result in classification errors of as much as 40%. Though classification results are similar between spherical and adaptive PCA models, spherical models use many small identical components to represent data. This is problematic since the number and characteristics of classes cannot be easily determined from the spherical model. In contrast, our adaptive PCA models accurately identify both the number and characteristics of classes, e.g. image textures, as shown in our experimental results.

Bias and Covariance of Dynamic PET images Reconstructed From Listmode Data

Evren Asma, USC

(Evren's abstract here)

Decoupling the Equations of Regularized Tomography for Scalable Parallel Computations

Jonas August, Carnegie Mellon University

Deferring discretization can occasionally change our perspective on imaging problems. To illustrate, we offer a reformulation of regularized computed tomography (CT) in which the large system of coupled equations for the unknown smoothed image is decoupled into many smaller and simpler equations, each for a separate projection. Regularized CT thus becomes a two-stage process of (nonhomogeneous) smoothing of the projections followed by filtered backprojection. As a by-product, the repeated forward and backprojections common in iterative image reconstruction are eliminated. In addition, the separate projections can be computed in parallel, and we demonstrate linear speedup on 20 processors. Despite the computational simplification, we demonstrate that this method can be used to reduce metal artifacts in X-ray CT images. The decoupling of the equations results from postponing the discretization of image derivatives that realize the smoothness constraint, allowing for this constraint to be analytically "transferred" from the image domain to the projection, or Radon, domain. Our analysis thus clarifies the role of image smoothness: it is an entirely intra-projection constraint.

Generation and Analysis of Textures with Tree-Driven Gaussian and Levy-Stable Processes

Albert Benassi (Dep. de Mathematique - Un. Clermont II), Sebastien Deguy (LLAIC - Un. Clermont I), Marie-Eliette Dury (Labo. de Math. Appliquees - Un. Clermont II), Pascal Bleuyard (Labo. de Meteorologie Physique - Un. Clermont II), and Anthony B. Davis (LANL, Space & Remote Sensing Sciences Group)

A large class of textures can be seen as realizations of random stochastic processes. So generating a texture amounts to choosing a good random process while analyzing a texture is to identify a process as a good candidate. The solution we are actively pursuing is to use stochastic processes defined by a finite number of parameters, with the condition that these parameters are identifiable using suitable statistical estimators. In this way, a texture is mapped to a set of numbers, the parameters of the model.

Tumor Growth Image Analysis
Songhe Cai and Marios S. Pattichis, UNM

In this paper, we study the problem of estimating tumor growth from planar images such as those generated by CT or MRI imaging systems. Tumor growth is estimated from a time sequence (a longitudinal study) of corresponding 3D slices of the tumor. We model image artifacts arising from patient breathing during scanning in terms of rigid body transformations of the imaged tumor. Following rigid body registration, we apply modified optical flow equations to estimate the tumor deformation vector field. Actual tumor growth is estimated in terms of the divergence of the deformation vector field, and the principal axes of growth are estimated at every point in the tumor. The approach allows us to measure and characterize tumor growth locally.

Total Variation Regularization of Proton Radiographic Inversions
Patrick Campbell, Kevin R. Vixie, Tom Asaki, and Neal Martin, LANL

In this paper, we demonstrate the effectiveness of TV minimization in the reduction of noise and reconstruction artifacts. We comment on the non-uniquess of the un-regularized TV minimization problem (in the radiographic case) and discuss current topics of study.

Topology Preserving Active Contours
Tom Cecil, UCLA

One of the main advantages of the Eulerian framework of level set front tracking is the ability of the front to change topology without "emotional involvement", or without any change in the algorithm being used to evolve the front. However, in certain cases it may be desirable to keep fronts from merging or breaking while using level sets. Some examples are in medical image segmentation, where tissues such as skin or the surface of the brain are thought of as topologically equivalent to a sphere. Here we introduce a coupled set of PDEs that govern the motion of a segmenting function while preserving its initial topology. This is joint work with S. Osher, P. Thompson and L. Vese.

Neutron Imaging for Inertial Confinement Fusion
C. R. Christensen, C. Barnes, G. L. Morgan, M. Wilke, and D. C. Wilson

Inertial confinement fusion involves the use of lasers to implode a tiny capsule filled with hydrogen isotopes in order to achieve nuclear fusion. Because of the high energy density (10 keV) and short times (tens of psec), burn diagnostics must rely on the passive receipt of radiation (protons or neutrons). Neutrons are especially difficult to use in imaging because of their small cross section for interaction. A "pinhole" imaging system must use a hole in a body that is many centimeters thick, and still suffers from a broad point-spread function. Scintillation detectors have low sensitivity, so that the signal is spread out and noisy. We have developed a mathematical procedure to enhance resolution. It is based on the accurate calculation of the point-spread function in matrix form, singular value decomposition, and constrained optimization. We will show both simulations and real data from experiments on the OMEGA laser facility.

Segmentation with depth: Minimizing the Nitzberg - Mumford - Shiota Energy

Selim Esedoglu, UCLA

Given an image that depicts a scene with several objects in it, the goal of segmentation with depth is to automatically infer the shapes of the objects and the occlusion relations between them. Nitzberg, Mumford, and Shiota formulated a variational approach to this problem: the solution is obtained as the minimizer of an energy. We describe a new technique of minimizing their energy that avoids explicit detection/connection of T-junctions. Joint work with Riccardo March.

Optical Mapping and DNA Fragment Sizing of Bacterial Genomes by Fluorescence Microscopy

Matthew M. Ferris, Cheryl L. Lemanski, Babetta L. Marrone, Thomas M. Yoshida and Richard A. Keller, Los Alamos National Laboratory, B-Division

Restriction Fragment Length Polymorphism (RFLP) digest, with DNA fragment sizing by Pulsed Field Gel Electrophoresis (PFGE), is the most common method currently used for bacterial identification at the species and strain level. However, PFGE relies on the availability of large amounts of pure sample, a condition not typically met by samples for applications including anti-bioterrorism, forensics and food safety. PFGE is therefore reliant on culturing methods and/or PCR to produce the quantity of sample required for analysis. Previously, our group has demonstrated bacteria genome fingerprinting by flow cytometry (Huang, et al.) which, for large fragments, was shown to be more sensitive (sample size of femtograms vs. micrograms), faster (analysis time reduced by more than 60 fold), and more accurate (size uncertainty of 2% vs. 10%) than PFGE. While this flow cytometry technique has clear advantages, it is still limited by sample requirements. To eliminate the need for sample amplification by PCR or culturing, we have begun to develop methods capable of identifying bacteria based upon analysis of individual cells. This technique utilizes in-situ sample preparations of cells embedded in an ultra-thin gel mounted to a solid substrate. Cell lysis, protein digestion, restriction of DNA fragments, and fluorescence staining of DNA fragments is accomplished by diffusion of reagents into the gel matrix. Resulting RFLP fragments are separated with an electrophoretic field and imaged with a microscope based, high sensitivity fluorescence imaging system. Quantitative analysis of resulting images has produced histograms of DNA fragment size distributions similar to those produced by flow cytometry. Additionally, poly-L-lysine derivatized substrates have been utilized to conduct optical mapping studies which will provide fragment ordering information not obtainable from either PFGE or flow cytometry.

Bifurcations of fourth-order traveling waves in image processing
John Greer, Duke

Digital image inpainting has recently become a popular topic in PDEs and image processing. A number of different equations combining nonlinear advection and anisotropic diffusion have been suggested for image inpainting. While excellent results have been produced, little is known mathematically about the relationship between advection and anisotropic diffusion. The authors study two nonlinear advection-diffusion PDEs inspired by image inpainting. Both are in one space dimension and combine a Burgers type advection term with a form of anisotropic diffusion. One has a second-order anisotropic diffusion term of the type introduced by Perona and Malik, and the other has a fourth-order anisotropic diffusion term. We study traveling wave solutions of the PDEs that approach fixed values u_L and u_R at $+-\infty$. We prove the existence of traveling waves for the second-order PDE, and give numerical evidence of traveling wave solutions of the fourth-order PDE. We show that in both cases these traveling waves only exist for u_L and u_R sufficiently close to each other.

Clustering Ultrasound Images by using Mutual Information
Feng Huang, University of Florida

An information-theoretic approach is presented for clustering echocardiographic images. The technique uses the Geometric Entropy to define the distance between images and does not require that the image intensities are linearly related. A method for averaging a set of images, based on maximizing mutual information, is also introduced.

Seismic Imaging of the Earth's Interior
Lianjie Huang, Michael Fehler, Hongchuan Sun, and Doug Alde, LANL

Imaging of the Earth's interior is vital to natural resource exploration. The integral structures of the Earth can be obtained using seismic migration imaging, that is, backpropagating seismic data recorded on the surface into the Earth to obtain the geometrical structures of interfaces. Most seismic migration algorithms widely-used in industry are based on the Kirchhoff integral solution of wave equation in which the Green's function is obtained using ray tracing. It is difficult for Kirchhoff migration to accurately image complex structures where wave phenomena are complicated and ray tracing could be inaccurate. We have developed new migration imaging methods based on solutions of one-way wave-equation for downward continuation of wavefields. These wave-based methods can easily handle complex wave phenomena more accurately than the ray-based Kirchhoff migration. They produce more accurate and clearer images of complex structures than Kirchhoff migration.

Invariant Conformal Mapping of Cortical Surfaces
Anand Joshi and Richard Leahy, University of Southern California

(Anand's abstract here)

Tomographic Reconstruction of Brief Temporal Phenomena
Doug Johnson, Bechtel Nevada Los Alamos Operations

(Doug's abstract here)

Design and analysis of a robust image registration method
Jeongtae Kim and Jeffrey A. Fessler, University of Michigan

We have investigated the statistical properties of intensity-based image registration methods, specifically their mean, variance and robustness. The sample correlation based method is highly efficient for intra-modality registration, but is very sensitive to outliers in the data. We have proposed a robust correlation coefficient image registration criterion, and show that it improves robustness to outliers with only modest degradation of statistical efficiency in the absence of outliers. The proposed robust method can have better statistical efficiency than the mutual information method for intra-modality registration. We have compared the statistical properties of the proposed method, the sample correlation coefficient method, and the MI-based method by theoretical analysis, computer simulations, and a phantom experiment.

Imaging Methods in Mobile Sensor Algorithms
Dan Marthaler, Duke

(Dan's abstract here)

Man-made Object Detection Algorithm
Lakshman Prasad and Alexei Skourikhine, LANL

We present an algorithm for detecting man-made objects using structural properties of object shapes. The algorithm consists of an efficient, noise-resistant contour compression scheme that extracts salient points of the contour of an object's digitized shape. This yields a polygonal approximation of the object's contour, which is then used to obtain contour and region-based characterization, in terms of linearity and local symmetry, respectively, of the 'man-madeness' of the object. The latter characterization is obtained by performing a nonlinear thresholding and summation of the significant linear and symmetric components of the shape. The algorithm has important applications to satellite and airborne reconnaissance, video surveillance, automatic target recognition, and many other image understanding applications. The contour compression part of the algorithm alone has several important applications in image processing and computer vision.

Feature Extraction from Hyperspectral Images Compressed Using the JPEG-2000 Standard
Mihaela D. Quirk, Christopher M. Brislawn and Steven P. Brumby - LANL

We present results quantifying the exploitability of compressed remote sensing imagery. The performance of various feature extraction and classification tasks is measured on hyperspectral images coded using the JPEG-2000 Standard. Spectral decorrelation is performed using the Karhunen-Loeve Transform and the 9-7 wavelet transform as part of the JPEG-2000 process. The quantitative performance of supervised, unsupervised, and hybrid classification tasks is reported as a function of the compressed bit rate for each spectral decorrelation scheme. The tasks examined are shown to perform with 99% accuracy at rates as low as 0.125 bits/pixel/band. This suggests that one need not limit remote sensing systems to lossless compression only, since many common classification tools perform reliably on images compressed to very low bit rates.

Dynamic Programming in Cortical Surface Analysis
Tilak Ratnanather, Johns Hopkins University

We have been developing automated methods in the cortical analysis of highly convoluted brain substructures such as the medial prefrontal cortex and the planum temporale which are respectively implicated in major depression disorders and speech/language processing disorders. In particular, we focus attention on the application of dynamic programming in generating principal gyral and sulcal curves on cortical surfaces leading to definition of coordinate systems on submanifolds. Such coordinate systems will permit comparison of brain substructures in understanding neuropsychiatric diseases.

Using Image Analysis to Refine Numerical Simulation Techniques for Shock-Induced Mixing
William J. Rider, James R. Kamm, Christopher D. Tomkins, and Mark Marr-Lyon, LANL, LANL

Validation of numerical simulations, i.e., the quantitative comparison of calculated results with experimental data, is an essential practice in computational physics. These comparisons are particularly difficult in the field of hydrodynamic instabilities and turbulence. The flows we consider are dominated by irregular structures, induced by the passage of a shock wave, that exhibit non-deterministic behavior. As there is no way to establish meaningful direct (i.e., pointwise) correspondence between experimental data and numerical simulation results, we appeal to indirect (i.e., statistical) methods using image analysis techniques, such as fractal characterization and wavelet spectra, to gauge simulation fidelity and ultimately guide simulation algorithm development. Specifically, we perform numerical calculations motivated by the experimental data for a diffuse cylinder of sulfur hexaflouride in air that evolves after the passage of a Mach 1.2 shockwave. These simulations are based on the Richtmyer-Meshkov (RM) experiments performed here at LANL as well as at the University of Arizona. Using the spectral measures mentioned above, together with simple integral-scale metrics, we examine the effect of the numerical algorithm by which the governing equations, the Euler equations of gas dynamics, are discretized.

Fast Global Projection-Based Methods for Affine Motion Estimation
Dirk Robinson and Peyman Milanfar, UCSC

The demand for more effective compression, storage, and transmission of video data is ever increasing. To make the most effective use of bandwidth and memory, motion-compensated methods rely heavily on fast and accurate motion estimation from image sequences to compress not the full complement of frames, but rather a sequence of reference frames, along with differences between these frames which results from estimated frame-to-frame motion. Motivated by the need for fast and accurate motion estimation for compression, storage, and transmission of video as well as other applications of motion estimation, we present algorithms for estimating affine motion from video image sequences. Our method utilize properties of the Radon transform to estimate image motion in a multiscale framework to achieve very accurate results. We develop statistical and computational models that motivate the use of such methods, and demonstrate that it is possible to improve the computational burden of motion estimation by more than an order of magnitude, while maintaining the degree of accuracy afforded by the more direct, and less efficient, 2-D methods.

Fast Computation of Multidimensional Discrete Fourier Transforms on Modern Single Instruction Multiple Data (SIMD) Architectures
Paul Rodriguez V. and Marios S. Pattichis, UNM

A general framework to develop efficient single Instruction Multiple Data (SIMD) compliant algorithms was recently developed. In this framework, efficient implementations to compute single and multidimensional Discrete Fourier Transforms (DFTs) have been developed. The new algorithms, called SIMD-FFTs, were found to be faster than any other scalar or SIMD-aware implementation. In addition, the algorithms have been extended to allow us to compute multidimensional DFT spectra along user-specified spectrum directions. When used to compute the entire DFT spectrum, the new directional algorithms are found to be more accurate.

Recently, this framework has been used to implement a parallel SIMD-FFT algorithm, targeted for both the shared memory and the network parallel models. One of the main features of this approach is that it exhibits two levels of parallelism: one due to instruction level parallelism within each processor, and the other due to the number of parallel processors. Preliminary results tested on Azul (Albuquerque High Performnace Computer Center's parallel computer with 32 Xeon processors) show that this approach scales with the number of processors.

VESTA - a novel Volume Enclosing Surface exTraction Algorithm
Bernd R. Schlei, LANL

We present a novel algorithm that generates surfaces for voxel data. A voxel is a unit of graphic information that defines a point in three-dimensional space, analogical to a pixel being a unit of graphic information that defines a point in two-dimensional space. The volumes, which are enclosed by the surfaces are always larger than zero, and the constructed surfaces are always nonselfintersecting. The Volume Enclosing Surface exTraction Algorithm (VESTA) is a straightforward generalization of the DIlated CONtour EXtraction (DICONEX) algorithm for two-dimensional image blobs. In this presentation, the usefulness of VESTA is demonstrated through its application to a diverse range of three-dimensional data sets: (i) Remote Ultra-Low Light Imaging (RULLI) range data, for the purpose of three-dimensional structural characterization; (ii) proton Radiographic (p-Rad) single view frame sets, for the purpose of determining, e.g., velocity fields of temporally evolving burn regions in high-explosives experiments; and (iii) temporally evolving density regions from hydrodynamical simulations of ultra-relativistically expanding fireballs, for the purpose of freeze-out hypersurface extractions for subatomic multi-particle production.

TBA
Larry Schultz, LANL

(Larry's abstract here)

TBA
David Strong, Pepperdine University

(David's abstract here)

Quantification of Damage From Incipient Failure Experiments
W. Rich Thissell, LANL

Structure-Property Relationships Los Alamos National Laboratory Explicit models of damage and fracture for use in integral codes have internal state variables such as porosity and volumetric number density of damage features such as cracks and/or voids. The magnitude of these variables evolves as damage is accumulated in the material. Model development, validation, and verification, as well as determination of model parameters for specific materials require simulations of incipient failure experiments and a comparison between simulated and experimental values of these variables. The subject of this poster is the methods used to obtain descriptors of damage in microstructures obtained from incipient failure experiments. The methods involve image analysis of a metallographic section plane, feature identification and measurement, and feature fitting to an arbitrary ellipsoid using optical profilometry data. The resulting lists of features have characteristics that are inherently statistical in nature and are reduced to descriptors amenable to comparison with deterministic macroscopic simulations.

Innovative analysis of experimental concentration and velocity field data in a shock-driven instability problem.

C. Tomkins, M. Marr-Lyon, K. Prestridge, P. Rightley and R. Benjamin. DX-3, Los Alamos National Laboratory and P. Vorobieff, University of New Mexico

We apply a suite of analyses to experimental concentration and velocity field data for a problem in Richtmyer-Meshkov instability. The instability is created by the interaction of a planar shock with one or two cylinders of dense gas (SF6) in air. The concentration field is captured with laser-sheet visualization immediately before shock impact and at six times after shock impact, and one planar, high-resolution velocity measurement is obtained at late time using particle image velocimetry (PIV). The large and intermediate scales of the post-shock flow are deterministic and dominated by counter-rotating vortex pairs. At late time, however, a secondary instability increases activity on the smaller scales, which are stochastic in nature, and initiates a transition to turbulence and subsequent mixing. Structure functions are used to provide evidence of this transition and compared with theory for fully turbulent flow. A correlation-based ensemble averaging procedure is introduced that permits decomposition of the flow field into deterministic and stochastic components.

Chaos quantification in low-Re mixing flow

P.Vorobieff, A.Mammoli and R. Truesdell, University of New Mexico

(Peter's abstract here)

Template Matching with Local Invariance
Brendt Wohlberg and Kevin Vixie, Los Alamos National Laboratory

In the majority of template matching applications, the measure of match is desired to be invariant to certain transforms (such as rotation and scaling) of the template. A variety of solutions have been proposed, the majority of which are designed for specific transforms with respect to which invariance is required, and often involve significant computational demands. We propose utilizing local linear approximations to these transforms, providing invariance to "small" transformations of the template without significantly increased computational requirements.

Computer Observer Detection Performance from Statistically Reconstructed Tomographic Images
Anastasia Yendiki and Jeffrey A. Fessler, University of Michigan

Several types of medical diagnosis involve the detection of an abnormality in an image reconstructed from noisy tomographic data. Faced with choosing among a plethora of image reconstruction methods, one would like to find which method best facilitates the detection task. Using fairly simple models for the signal detection task and assuming linear observers, we have derived analytical expressions for observer performance (as described by SNR) for a broad family of linear image reconstruction methods. Since the exact SNR expressions require prohibitively large computation, we have developed and evaluated approximations using frequency-domain concepts. These approximations provide a means of comparing tomographic image reconstruction methods with modest computation. For the case of penalized-likelihood tomographic image reconstruction, one can use these SNR approximations to choose the value of the regularization parameter that maximizes the SNR. For some tasks and observers, our analysis shows that regularization is surprisingly unimportant.

3-d Object Reconstruction using Tracking of Freehand Ultrasound
Honggang Yu, Marios S. Pattichis, and M. Beth Goens, UNM

In freehand ultrasound imaging, a sonographer is allowed to position and orient an ultrasound transducer so as to obtain optimal views of the imaged objects. Freehand 2-D ultrasound systems can be converted to inexpensive 3-D ultrasound system by adding an electromagnetic 3-D position and orientation sensor that is used for tracking the transducer position and orientation.

A new detector system is used for detecting whether the system is making reliable estimates of sensor position and orientation. The detector system is based on new methods for estimating the probability density functions of the error in the sensor position and orientation measurements. The detector system is used to detect regions where there is unwanted electromagnetic interference.

A least-squares method is developed for correcting errors in the sensor measurements. The method is based on correcting the trajectories of the sensor position and orientation estimates. The methods are applied and validated on the 3-D reconstruction of ultrasound phantom targets.